WHITE-NOSE SYNDROME: AN EMERGING DISEASE AND A POTENTIAL THREAT TO MEXICAN BATS

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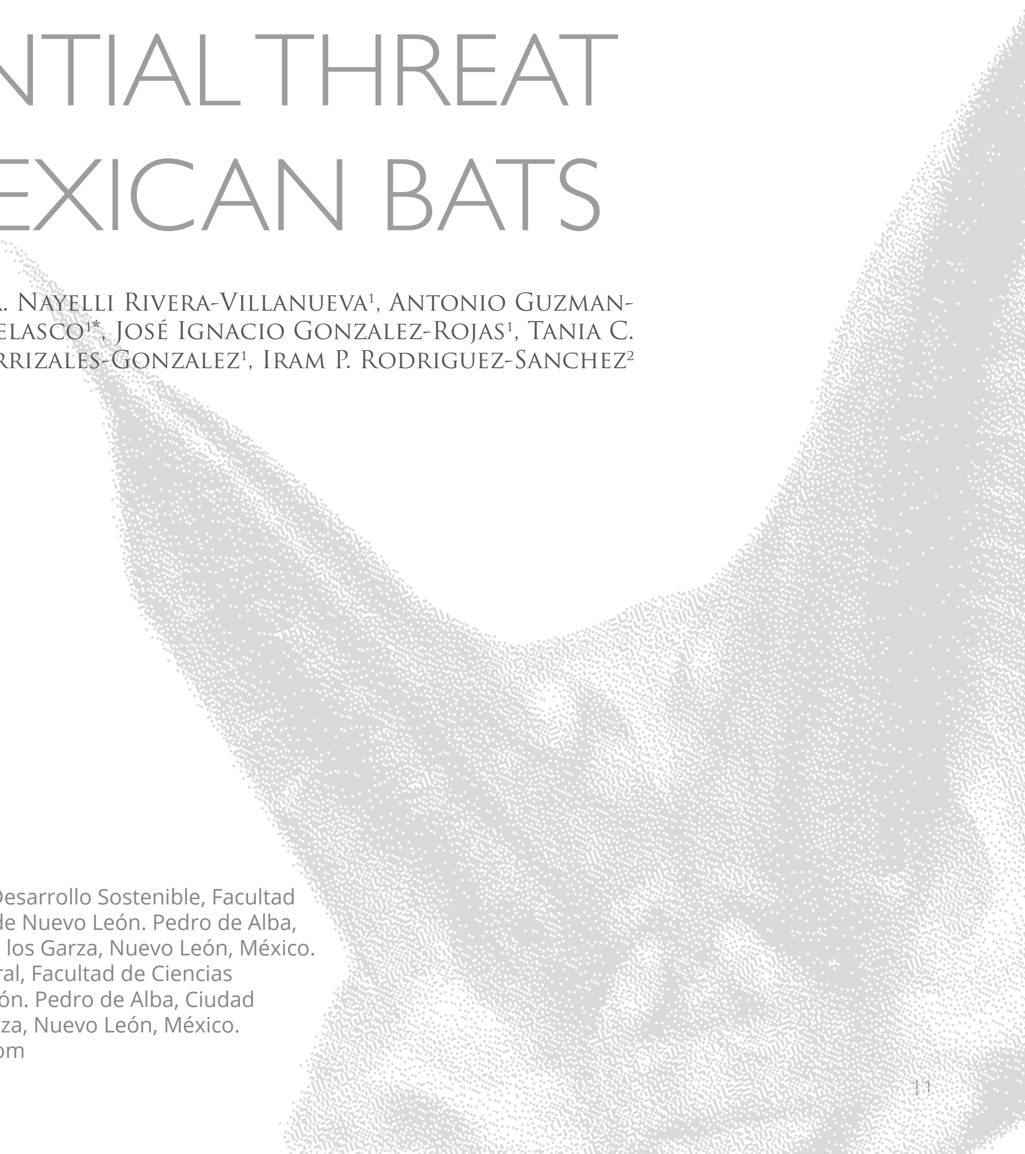

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Abstract

Currently, in North America, several hibernating bat species are threatened by the disease White-Nose Syndrome (WNS), caused by the fungus *Pseudogymnoascus destructans*. This disease proliferates during the winter season as it infects bats during hibernation, affecting bat populations in the U.S. and Canada. Since its detection in 2006, it has caused an estimated number of more than 6 million deaths. Mexico shares several hibernating bat species with the U.S. and Canada, many of which have tested positive for the fungus. *Eptesicus fuscus*, *Myotis sodalis*, *Myotis lucifugus*, and *Perimyotis subflavus* have experienced dramatic population declines because of WNS. For example, *Myotis velifer*, *Myotis evotis, Corynorhinus* sp., get infected, but the effects on their populations have not been widely studied. Efforts to estimate the impact of WNS in the United States and Canada have shown alarming trends, with declines of up to 90% in some species. No equivalent studies have been conducted in Mexico, leaving the country vulnerable to the potential spread of WNS. Here we show that proactive monitoring and mitigation strategies are crucial to prevent the introduction and spread of WNS in Mexican bat populations. Our goal is to make an urgent call for research on the WNS and understand the environmental conditions within hibernacula and the vulnerability of local bat species. Without effective interventions, Mexican bat populations could face catastrophic declines. Understanding local populations could help species that are already affected. It is necessary to begin monitoring in Mexico to detect its presence before it spreads to other areas.

Resumen

Actualmente, en Norteamérica, algunas especies de murciélagos hibernantes se encuentran amenazados por la enfermedad Síndrome de la Nariz Blanca (SNB), causada por el hongo *Pseudogymnoascus destructans*. Esta enfermedad prolifera durante la estación invernal, infectando a los murciélagos durante la hibernación, lo que afecta a las poblaciones de murciélagos hibernantes en Estados Unidos de América y Canadá. Desde su detección en 2006, ha causado la muerte de más de 6 millones de murciélagos. México comparte varias especies de murciélagos hibernantes con Estados Unidos y Canadá, muchas de las cuales ya han dado positivo al hongo. *Eptesicus fuscus, Myotis sodalis, Myotis lucifugus* y *Perimyotis subflavus*, han experimentado una drástica disminución de sus poblaciones a causa del SNB. Por ejemplo, *Myotis velifer*, *Myotis evotis, Corynorhinus* sp., se infectan del hongo, pero los efectos en sus poblaciones no han ampliamente estudiados. Los esfuerzos para estimar el impacto del SNB en Estados Unidos y Canadá han mostrado tendencias alarmantes, con descensos de hasta el 90% en algunas especies. En México no se han realizado estudios equivalentes, por lo que el país es vulnerable a la posible propagación del SNB. Aquí mostramos que las estrategias proactivas de monitoreo y mitigación son cruciales para prevenir la introducción y propagación del SNB en las poblaciones de murciélagos mexicanos. Nuestro objetivo es hacer un llamado urgente para la búsqueda del SNB y entender las condiciones ambientales dentro de los hibernáculos y sobre la vulnerabilidad de las especies locales de murciélagos. Sin intervenciones eficaces, las poblaciones mexicanas de murciélagos podrían sufrir declives catastróficos. Entender nuestras poblaciones locales podría ayudar a conservar las especies que ya están siendo afectadas. Es necesario iniciar el monitoreo en México para detectar su presencia antes de que se extienda a otras áreas.

Keywords: Chiroptera, fungus, mycosis, mortal, *Pseudogymnoascus destructans*.

Palabras clave: Chiroptera, hongo, micosis, mortal, *Pseudogymnoascus destructans*.

INTRODUCTION

General information about bats

Bats constitute the second-largest order of mammals, with more than 1,470 species worldwide (Simmons and Cirranello, 2024). They belong to the order Chiroptera and are the most widely distributed terrestrial group, representing about 20% of the class Mammalia (Fig. 1). They have evolved the ability to detect, locate, and classify objects for movement, feeding, and communication through echolocation (Metzner, 1991). The great diversity and adaptations that bats possess are mainly reflected in the ecosystem services they provide, such as pollination, seed dispersal, insect control, and in the multiple ecosystems where they are distributed (Fig. 2). Currently, 147 species of bats have been reported in Mexico representing eight families (Simmons and Cirranello, 2024). In the case of Mexico, diversity of bats can be listed as insectivorous, fruit-eating, nectarivorous, omnivorous, carnivorous, and piscivorous species (Kunz et al., 2011). Despite their importance in ecosystems, approximately 80% of bat species worldwide require some degree of conservation actions or research due to threats and information gaps (Frick et al., 2020). Bat assemblages face major threats such as habitat loss, climate change, disturbance of their roosts, and emerging diseases such as White Nose Syndrome (WNS), a deadly disease in bats, that is causing millions of deaths in North America (Hoyt et al., 2021). Undoubtedly, WNS threatens the conservation of bats and the ecosystem services they provide.

Figure 1. Colony of cave bats in the south of Nuevo León, Mexico. This emergence shows a large number of bats that the can have the caves in the north of Mexico. Photograph by Ricardo Quirino.

Figure 2. An example of the northern ecosystems in Mexico where cave-dwelling bats forage. Photograph by Ricardo Quirino.

Importance of bats in Mexico

The diversity of ecological niches and different tropic guilds constitute a wide range of ecosystem services. Insectivorous bats play an important role in maintaining the stability of natural ecosystems, controlling insect pest populations, preventing crop loss, and consuming arthropods that may be vectors of medically important diseases (Kunz et al., 2011). Fruit bats contribute to seed dispersal, which increases forest diversity and in disturbed or deforested areas are responsible for introducing new plants, reducing habitat fragmentation (Ghanem and Voigt, 2012). Nectarivorous bats feed mainly on flower nectar, allowing gene flow of several plant species such as agaves (Kunz et al., 2011) (Fig. 3). In addition, bat guano is the main organic matter in some subterranean ecosystems and can be used as a natural fertilizer (Kunz et al., 2011; Ramírez-Fráncel et al., 2022).

The ecosystem services primarily affected by this syndrome are those provided by insectivorous bats (Hoyt et al., 2021). Adequate quantification of the impact on arthropod communities from declines in bat populations affected by WNS in the U.S. and Canada has not been conducted. However, an increase in arthropod vectors of diseases such as mosquitoes and pests that will reduce crop yields including defoliating moths, and beetles, among other species is predicted (Hoyt et al., 2021; O'Keefe et al., 2019).

Furthermore, preliminary data in the U.S. have suggested an increase in pesticide use since the first impacts of WNS were observed and this phenomenon has been linked to an increase in infant mortality (Frank, 2024). In Nuevo León, northern Mexico, a colony of the insectivorous species, *Tadarida brasiliensis*, was evaluated for its economic value in allowing the reduction of agrochemical application by controlling arthropod pests in sorghum, walnut, and corn crops, giving a value between $6.5 and 16.5 million Mexican pesos per hectare per year (Gándara et al., 2006). Profit from tourism activity has been calculated in multiple bat roosts that host up to millions of individuals of the species *Tadarida brasiliensis* located in the U.S., obtaining around 6.5 million dollars per year (Bagstad and Wiederholt, 2013). The main beneficiaries in these cases are local people who depend on activities such as agriculture, trade, and tourism to generate economic

Figure 3. Example of one of the agaves (*Agave angustifolia*) that bats pollinate. Photograph by Ricardo Quirino.

income. With the threat of WNS, we not only face challenges in bat conservation but also consequences that would affect communities surrounding the refuges and their economic activity.

White-Nose Syndrome

It is an invasive mycosis affecting hibernating bats (Fig. 4) and is caused by the fungus *Pseudogymnoascus destructans* (*Pd*) (Blehert et al., 2009; Minnis and Lindner, 2013). The name of the disease comes from the growth of the fungus on the skin surface around the snout, ears, and wing membrane of bats (Chaturvedi et al., 2010). This disease has only affected bats in North America, as *P. destructans*-positive individuals in Eurasia, do not show significant mortality, due to co-evolution (Turner et al., 2011). Through phylogenetic studies, it was determined that the fungus originates from Eurasia, and the genetic characteristics of the fungus indicate that its introduction to America was probably by anthropogenic activities and not by natural spread (Drees et al., 2017; Leopardi et al., 2015). It was first documented in the state of New York in 2006 and has since spread uncontrollably throughout the U.S. and Canada (Blehert et al., 2009; Hoyt et al., 2021). It is estimated that the fungus infection has killed more than 6 million hibernating bats (Wibbelt, 2018). In some cases, it has caused the reduction of bat colonies by 90%, to their complete disappearance (Turner et al., 2011).

P. destructans, infects bats when they enter the roosts to hibernate and invade the integuments altering their natural state of torpor, leading to their death due to lack of energy (Lilley et al., 2016; Reeder et al., 2012). *P. destructans* can be transmitted by direct contact between bats or when a bat arrives where the fungus has become established (Lorch et al., 2012). When spores of the fungus enter a cave (Fig. 5), it becomes highly infectious and can survive for several years even after the bats had gone (Frick et al., 2017). Therefore, positive samples either by biopsies or swabs from bats in a roost are conclusive evidence for the presence of WNS in the entire roost and probably in all of its individuals (Campbell et al., 2020; Frick et al., 2017).

The integuments infected with *P. destructans* gradually deteriorate due to the activity of the fungus that invades and digests the surface of the bat, causing a reduction in the elasticity and width of the skin, and in the final stages, ulcers and tissue loss may occur. Tissue loss compromises proper thermoregulation of the bat and can cause an extensive inflammatory reaction (Cryan et al., 2010; Meteyer et al., 2012). Destruction of dermis components such as sebaceous/sudoriferous glands and blood vessels results in an inflammatory reaction, fluid loss, and vulnerability to microbial infections (Reichard and Kunz, 2009; Warnecke et al., 2013). An infection caused by the fungus could cause fever in the bat and promote premature fat depletion (Mayberry et al., 2018). These alterations lead to several responses

Figure 4. *Corynorhinus sp.* in torpor. As a scale of the body size, the measurement of the forearm was 43 mm. Photograph by Ricardo Quirino.

Figure 5. Set of caves, home to bats in Nuevo León state in the Chihuahuan Desert. Photograph by A. Nayelli Rivera-Villanueva.

at the physiological level such as the disruption of blood pH autoregulation in the wing membrane (Davis, 1988), as well as the secretion of endopeptidases that degrade collagen, leading to greater tissue ulceration and elevated CO_2 concentrations (O' Donoghue et al., 2015). Both responses may result in metabolic acidosis, and when combined with fluid loss-induced hypotonic dehydration, can lead to an early awakening of the bat from hibernation (Cryan et al., 2013; Magnino et al., 2021). The imbalance in bat blood homeostasis affects the duration of hibernation, increasing the frequency at which the individual awakens (Magnino et al., 2021).

Mortality from White-Nose Syndrome

Bats that awaken during the hibernation season due to WNS are more likely to exhibit higher mortality rates as compared to those bats that awaken less (Lilley et al., 2016). Increased short torpor periods due to frequent awakenings induces bats to consume their energy reserves more rapidly (Reeder et al., 2012). During these active periods, the bat attempts to obtain water, and food or find other shelter, but the degraded state of the wings makes this task more difficult, coupled with the low availability of food during the winter, creating a deadly situation for the individual (Cryan et al., 2010). The few bats that manage to survive WNS often experience considerable damage that persists even after several months, such as deteriorated wings and extremely low body fat, which decreases their success during foraging and future reproductive success (Hallam and Federico, 2012; Reichard and Kunz, 2009).

Since the emergence of WNS, multiple studies have estimated the impact it has had on bat populations. For example, mortality studies of some species since the first detection of the fungus in 2006 show how populations of *Eptesicus fuscus* (Big brown bat) have declined by 35%, *Myotis sodalis* (Indiana bat) populations have declined by 84%, while *Myotis septentrionalis*, *Perimyotis subflavus* (Tricolored bat) (Solari, 2019) and *Myotis lucifugus* (Little brown bat) have shown declines by up to >90%, (Cheng et al., 2021). A maternity roost of *M. lucifugus* was studied to determine the impact of the disease on its population. It was found that before the arrival of *P. destructans*, the bat colony was growing steadily, but after 4 years of being affected by WNS the colony had lost up to 90% of its population. Furthermore, it has been projected that, if conditions continue, in 16 years, *M. lucifugus* could be extinct (Frick et al., 2010). In a study where 42 hibernation sites were monitored, a drastic decrease in the number of hibernating bats was reported after WNS, going from 412,340 to 49,579 individuals of six species, representing a decrease of 88% (Turner et al., 2011). At least eight North American bat species are expected to experience an impact on their populations strong enough to categorize them as threatened in the following years because of WNS (Alves et al., 2014).

There have been multiple efforts to estimate the impact of WNS in the U.S., Canada, and other countries, but none have been carried out in Mexico. Since the presence of *P. destructans* and WNS was recorded in North America, a clear deterioration of hibernating insectivorous bat populations has been seen even though measures to mitigate the disease have already

Figure 6. *Corynorhinus townsendii* is one of the species of the genus (*Corynorhinus*) that have tested positive to the WNS. Photograph by Ricardo Quirino.

been implemented (Frick et al., 2010). Caves are the main roost option for hibernating bats because they provide a suitable microclimate and stable protection during low ambient temperatures (Humphrey, 1975). Due to the high interaction between members of a bat colony within a cave, 100% of these individuals tend to become infected with *P. destructans* during the hibernation season, then survivors may visit other caves and spread the fungus spores stored in their fur (Frick et al., 2017). This situation raises alarms about how populations in Mexico could be affected by this disease when it arrives or if it is already present in the country.

Bats with potential risk to the WNS

Bats vulnerable to WNS are those that hibernate, whether migratory or resident. Bats serve as connectors between localities separated by their ability to travel hundreds of kilometers each year in search of roosts, as well as by migration in some species. This phenomenon can be recorded in certain bat populations between the U.S. and Mexico (Wiederholt et al., 2013). These interactions play a key role in the rapid and widespread spread of *P. destructans* making Mexico highly susceptible (Gómez-Rodríguez et al., 2022).

Endothermic mammals such as bats can enter a state of torpor and hibernation, which results in decreased body temperature, reduced heart rate, slowed metabolism, and other physiological effects to maximize energy conservation during low energy seasons such as winter. Torpor is characterized by occurring over short periods, whereas hibernation involves multiple periods of torpor followed by an amplification of these physiological effects (Fritz, 2013). Also, during torpor, the immune system decreases its activity to save energy, leaving the bat vulnerable to infections such as WNS (Bouma et al., 2010).

Mexico shares with the U.S. and Canada some species of hibernating bats that have tested positive for the disease. The species in which WNS have been diagnosed with distribution in northeastern and northwestern Mexico are *Myotis evotis, Eptesicus fuscus, Myotis thysanodes, Myotis velifer, Myotis volans,* and *Myotis yumanensis*, which are at Least Concern (LC). While *Perimyotis subflavus* is vulnerable according to the IUCN (International Union for Conservation of Nature) and has distribution in the east of Mexico. The IUCN sets a list of threatened species in different categories according to their vulnerability to extinction; thus, an LC category shows that the species are not going to be extinct in the short term. On the other hand, the species positive for *P. destructans* that have been detected and that also have distribution in northeastern and northwestern Mexico are *Corynorhinus townsendii*, *Lasiurus borealis, Lasionycteris noctivagans, Myotis ciliolabrum, Tadarida brasiliensis, Parastrellus hesperus* (Gómez-Rodríguez et al., 2022; National Wildlife Health Center, 2022; White-Nose Syndrome Response Team, 2025; IUCN, 2024). In the case of *Tadarida brasiliensis*, although it seems that they are not clinically affected, they could serve as a bridge for the dissemination of *P. destructans* (National Wildlife Health Center, 2022). In addition, it is suspected that *Corynorhinus mexicanus* (Near Threatened according to the IUCN) and *Corynorhinus leonpaniaguae* (recently described), a species endemic to northeastern Mexico, could be vulnerable to the disease. This is because *P. destructans* has been detected in members of the same genus that also hibernate (Fig. 6).

Three species have been the main point of study due to the great affectations that the WNS has on their populations, *Myotis septentrionalis* (Near Threatened), *Myotis lucifugus (*Endangered), and *Perimyotis subflavus* (Vulnerable) according to the IUCN (Cheng et al., 2021). Of these three species, only *P. subflavus* is distributed in Mexico, ranging from southeastern Canada, extending through eastern Mexico to Honduras. A progressive decline in their populations has been detected since the detection of *P. destructans*. The first estimates in 2011 showed a 70% decline in its population (Turner et al., 2011), to a 90% decline by 2021 (Cheng et al., 2021). Predictions for *P. subflavus* showed that the impact would be limited to the northern U.S. and southern Canada. Still, the fatalities observed in the southeastern U.S. are comparable to those of *Myotis lucifugus* in the northeastern U.S. due to WNS (Loeb and Winters, 2022). In addition, for *M. lucifugus*, due to the high mortality because of WNS, projections estimate that in the next 16 years, it will be regionally extinct by up to 99% (Frick et al., 2010). In addition, it has not been recorded that populations are recovering in WNS-positive areas since the emergence of the disease (Perea et al., 2022). This indicates that the same possible outcome is expected for *P. subflavus* (Turner, 2011). This is aggravated by the rapid and progressive spread of the disease to the south of the U.S. Currently, the fungus already covers more than half of the distribution of *P. subflavus*, and continues to increase year after year (Cheng et al., 2021). With this information, we can predict the danger that the populations of this species are in Mexico, especially in the north of the country, a region that should be under special observation due to its proximity to areas with positive cases of WNS in the U.S. In addition, underground roosts are highly available in the region. The populations of *P. subflavus* that are most at risk are those that occupy underground roosts (Loeb and Winters, 2022). Thus, is worth mentioning that the highest number of fatalities has been found to occur in the first two years after the detection of the disease (Perea et al., 2022), which raises alarms of the great need for constant monitoring equipment if the disease is to be detected before it is too late.

It has been described that individuals of *P. subflavus* are beginning to prefer colder microclimate roots for hibernation. This may result in a strategy to survive WNS, as it helps to lower their metabolism during winter (Loeb and Winters, 2022; Turner et al., 2022). The possibility of migration of this species to new areas in search of roosts where it can survive is even suggested (Perea et al., 2022). If the *P. destructans* affects areas further south, such as Mexico, it could affect the distribution of this species, since its roosts in the country are warmer, increasing the probability of fatalities. However, there is a lack of information on where the vulnerable roosts in Mexico are located and their climatic characteristics (Krisko, 2020). Therefore, it is necessary to initiate strategies to locate and evaluate these refuges before the spread of the fungus is too late.

Underground roost environmental conditions and the growth of *Pseudogymnoascus destructans*

Environmental conditions within hibernacula (sites where bats enter torpor and hibernation) need to be evaluated because they can modulate the prevalence and impact of *P. destructans* on bats (Langwig et al., 2012). *P. destructans* is a psychrophilic fungus (Gargas et al., 2009). The main factors for the growth of the fungus are high humidity and temperate temperature (Langwig et al., 2012). The fungus prefers a relative humidity >90%. Its optimum temperature is between 12.5 °C and 15.8 °C, where it can grow and function normally. The decline of its colonies begins when the environment reaches its upper critical temperature between 19.0 °C and 19.8 °C. As the temperature increases, the morphology of the fungus changes, deforms, and is destroyed rapidly (Verant et al., 2012). The normal microscopic morphology of this fungus consists of curved conidia with a thick wall and an erect, hyaline, smooth, narrow, and thin wall (Chaturvedi et al., 2010; Blehert and Lankau, 2022). The temperature and humidity parameters preferred by the fungus are similar to those found in the roosts used during bat hibernation, moreover, such conditions are similar to those of the bat body during torpor (Cryan et al., 2010).

Spread of White-Nose Syndrome

Since its first record in 2006, the disease began to spread rapidly. In the first five years, its presence was reported in northern Maine, southern Alabama, and western Oklahoma (Maher et al., 2012). Just 3 years later, in 2010, it had also been detected in Vermont, Massachusetts, New Jersey, Connecticut, Pennsylvania, New Hampshire, Delaware, Virginia, West Virginia, Tennessee, Missouri, Oklahoma, Ontario, and Quebec (Foley et al., 2011). By 2014 it had advanced more than two thousand kilometers from its epicenter (Alves et al., 2014). Currently, WNS has been confirmed in 40 U.S.A. states and eight Canadian provinces, and new detections of *P. destructans* and WNS are reported each year (White-Nose Syndrome Response Team, 2025). The spread of WNS has exceeded all predictions made. States that were thought to be infected within decades have already been confirmed. The spread of the fungus is approximately 200-900 km per year, and it is expected that in the next few years, WNS will reach all or nearly all hibernacula in the U.S. and Canada (Hoyt et al.,

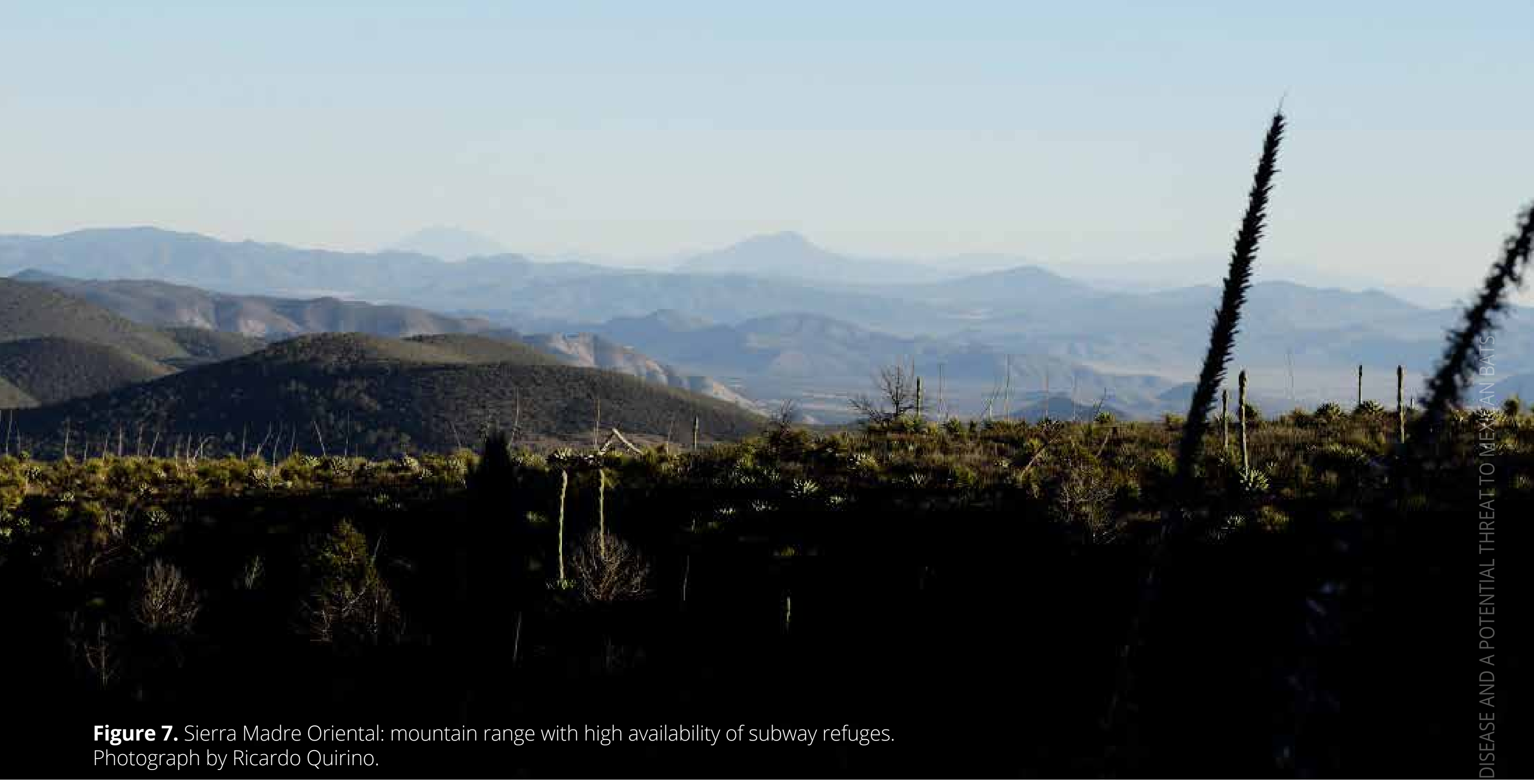

Figure 7. Sierra Madre Oriental: mountain range with high availability of subway refuges. Photograph by Ricardo Quirino.

2021). With such a wide and alarming spread it is difficult to think of a scenario in which Mexico would not be vulnerable to WNS if it borders the U.S.A. and shares some of the species already confirmed (Escobar et al., 2014).

To predict where WNS will be distributed in the future the climate outside and inside the roosts must be taken into account. The microclimate of the underground roosts (i.e., caves, mines, or lava tubes) depends on factors such as the depth of the roost, topographic elements, airflow patterns, and water infiltration, which can only be assessed *in situ*, limiting the possibility of making reliable projections (Perry, 2013). However, projections show that Mexico, due to climatic factors, has potential areas to host the WNS (Gómez-Rodríguez et al., 2022). Areas considered at risk can be monitored around the highlands including the Baja California Peninsula, Sierra Madre Occidental, Sierra Madre Oriental (Fig. 7), and the Trans-Mexican Volcanic Belt. This is because those regions maintain temperatures low enough for the proliferation and dissemination of *P. destructans* (Gómez-Rodríguez et al., 2022).

It was believed that bat colonies in more temperate regions such as Mexico would never develop the fungus, but cases such as those in South Carolina, Tennessee, Georgia, Alabama, and Texas, which have already been affected by WNS contradict this idea (Krisko, 2020). One reason is that *P. destructans* can survive in the skin of bats at temperatures up to 37°C for long periods. This allows *P. destructans* to spread in areas with temperate and even warm temperatures (Campbell et al., 2020).

In addition, it has been hypothesized that karst areas may serve as bridges for the spread of WNS. Most likely, *P. destructans* will be introduced to the karst regions of Mexico soon by migratory colonies of *Tadarida brasiliensis* (Krisko, 2020). Another way to predict the likely spread of WNS to Mexico is by examining the bat species shared with the U.S. that have tested positive for the disease. Although ecological niche modeling may be one way that could help predict the dispersal route of the fungus, it does not allow verification of presence, and fieldwork is necessary (Gómez-Rodríguez et al., 2022).

Final considerations

Today, Mexico continues without any positive records for *P. destructans* or WNS. There are a large number of caves in Mexico with similar climatic characteristics and with the same species that have been recorded as positive for WNS in the U.S. and Canada. It is therefore crucial to carry out monitoring to record its probable arrival, record its presence, and mitigate its spread before it can reach other roosts (Langwig et al., 2015; Bernard and McCracken, 2017; Campbell et al., 2020). We are currently facing a major problem due to the lack of information on the whereabouts of vulnerable hibernacula in Mexico for WNS. We show that proactive monitoring and mitigation strategies are crucial to prevent the introduction and spread of WNS in Mexican bat populations. We make an urgent call to search for the WNS and understand the environmental conditions within hibernacula and the vulnerability of local bat species. Without effective interventions, Mexico's bat populations could face catastrophic declines. It is necessary to start monitoring in Mexico to detect its presence before it spreads to other roosts.

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